

To appear in *The Astrophysical Journal*

Radio Continuum Emission from the Central stars of M20 and the Detection of a New Supernova Remnant Near M20

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ABSTRACT

The Trifid nebula (M20) is a well-known prominent optical HII region trisected by obscuring dust lanes. Radio continuum VLA observations of this Nebula show free-free emission at $\lambda 3.6$ and 6cm from three stellar sources lying close to the O7V star at the center of the nebula. We argue that neutral material associated with these stars are photoionized externally by the UV radiation from the hot central star. We also report the discovery of a barrel-shaped SNR G7.06–0.12 at the northwest rim of the nebula and two shell-like features G6.67–0.42 and G6.83–0.21 adjacent to W28 and M20. We discuss the nature of these features and their possible relationship to the pulsar PSR 1801-2306 and W28 OH (1720 MHz) masers.

Subject headings: galaxies: ISM—Galaxy: —ISM: individual (the Trifid Nebula) — ISM: HII regions

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1. Introduction

The Trifid Nebula (M20), one of the most spectacular optical HII regions in the sky, is centered on a small cluster of hot stars which include components A through G of HD 164492. M20 is located at a distance of ≈ 1.7 kpc in the Sagittarius spiral arm (but see also Kohoutek, Mayer & Lorenz 1999); its angular size of $6'$ corresponds to about 3pc at this distance. The ionizing flux of $10^{48.8} \text{ s}^{-1}$ required to maintain the HII region (Chaisson and Wilson 1975) is supplied by the O7.5III star HD 164492A (Wallborn 1973), which has $M_v = -5.3$ for $A_v \approx 1.3$ towards the central stars (Lynds and O’Neil 1985). This nebula is associated with the young star cluster NGC 6514 and a molecular cloud to the southwest (Ogura and Ishida 1975). The recent detection of several molecular condensations associated with protostellar sources in the HII region and HH 399, a remarkable jet-like structure, suggest a new generation of star formation induced by the nebula (Cernicharo et al. 1998). Hester et al. (1999) have recently shown the high resolution images of the SE corner of the nebula based on observations made with WFPC2 of the HST. The emission from this corner of the HII region is dominated by a photoionized photoevaporative flow.

M20 shows many similarities to M42 such as its interaction with its parent molecular cloud and its inhomogeneous nebular structure, but the Trifid is thought to be significantly younger than the Orion Nebula ($\sim 10^5$ yr rather than $\sim 10^6$ yr) and the protostellar molecular condensations associated with massive star formation are even younger (10^4 yr) (Cernicharo et al. 1998).

Here we present near IR and radio observations of M20. We have detected a number of near-IR stellar sources within the central star cluster in J, H, K and L images. All seven of the components of HD 164492 (A–G) appear to varying degrees in these images. Three components – B, C and D – coincide with compact radio continuum sources within 12 arcseconds of HD 164492A. These detections suggest that the central massive star is photoionizing the envelope of cool stars in its immediate vicinity similar to the “proplyds” in the Orion Nebula (Churchwell et al. 1987; Garay et al. 1987; O’Dell et al. 1993). Radio images of the nebula at 20 and 6 cm show dark features suggesting the presence of cold and dense regions of dust and gas clouds within the HII region shadowing the UV radiation from HD 164492A. Lastly, on a scale of tens of arcminutes, we report the discovery of a new candidate barrel-shaped supernova remnant (SNR) lying adjacent to M20 and two shell-type features to the north and east of SNR W28.

2. Observations

The Very Large Array of the National Radio Astronomy Observatory² was used in its compact C and D configurations at $\lambda 20$, 6 and 2cm in 1987 (Yusef-Zadeh et al. 1991). Follow-up high resolution observations in the wide BnA array were also carried out at 3.6, 6 and 20cm in 1998. In all observations 3C286 was used as standard amplitude calibrator and 1748-253 and 1730-130 as phase calibrators. The 2 and 6cm data were successfully self-calibrated in the BnA array configuration. The $\lambda 20$ cm and 6cm data corresponding to each configuration were combined before the final images were constructed using VTESS in AIPS. In order to measure the polarization characteristics of G7.06–0.12, we used a different antenna pointing at 6cm centered at $\alpha, \delta(1950) = 17^h 59^m 18^s, -22^\circ 55' 45''$ which is offset to the north of the central star HD 164492A.

Wide-field $\lambda 90$ cm observations towards the supernova remnant W28 which includes M20 were also

²The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.

obtained in the D configuration of the VLA in 1996. In this case 3C48 and 3C286 were used as amplitude calibrators, while 1828+487 (3C380) was used for phase calibration. The 90 cm data were processed using the wide-field imaging task DRAGON present in the NRAO Software Development Environment (SDE) reduction package. DRAGON successfully completed 5 loops of self-calibration and CLEAN-based deconvolution to generate the final $\lambda 90\text{cm}$ image.

J ($1.2\ \mu\text{m}$), H ($1.6\ \mu\text{m}$), K ($2.2\ \mu\text{m}$) and L ($3.5\ \mu\text{m}$) images were obtained in July 1995 using the near-IR array camera NSFCAM at the NASA Infrared Telescope Facility³. Due to the short time spent taking these images, some of the brighter stars were slightly saturated and stars fill the blank sky images. However, the main results presented here are not affected by the quality of the images.

3. Results and Discussion

3.1. Central Stars of M20

Figure 1 shows contours of 3.6cm emission with a resolution of $0.63'' \times 0.45''$ (PA= 80°) with $\text{rms} \approx 33\ \mu\text{Jy}$. Radio continuum peaks whose flux densities and sizes are listed in Table 1 coincide with the positions of HD164492 B, C and D. Optical positions of HD164492 A, B and C are also listed in Table 1 using the Hipparcos coordinates which are based on a fit to a multiple source model. The quality of the model solution for "C" using the Hipparcos database was poor, so we did not include it. However, there is an excellent agreement between the absolute position of radio and optical sources to within $0.1''$, especially for sources B and C.

The grayscale images in Figure 2 show the components of multiple star HD 164492 and are identified on the J image, which is very similar to visible images. The central star A coincides with the optical star HD 164992A but is not detected at a level of $\text{rms} \approx 33\ \mu\text{Jy}$ at 3.6cm. Source C, the brightest radio source, has a flux of 2.43 mJy at 3.6cm. HD 164492D lies only 2 arcsec west of star C and was found to be a strong H α emission source by Herbig, who classified it as a Be-star and named it LkH α 123 (Herbig 1957). It was also included as H α -emission star number 46 in a survey by Velge (1957) and star number 145 in the survey of Ogura and Ishida (1975). The D star is the brightest point source in recent 12.5 and 17.9 μm images that were taken with the JPL MIRLIN camera at the IRTF (Ressler and Shure 1995). Notice several objects in the L image which are either unseen or are very much dimmer shortward of K. Among these newly discovered sources is one roughly 3 arcsec NE and the other only 2 arcsec N of star A. If they are physically associated with this star ($2'' = 3400\ \text{AU}$ at 1.7 kpc), they would represent some of the first low-mass companions to high-mass stars.

All three sources B, C and D are also detected at 6cm based on our high resolution BnA array data. Accurate spectral index measurements between 6 and 3.6cm using similar uv coverage and spatial resolution of $0.99'' \times 0.7''$ (PA= -87°) showed $\alpha \approx 0$ for sources B and C and $\alpha = -0.19$, where $F_\nu \propto \nu^\alpha$, for source D. The D star as listed in Table 1 is the only star resolved in our 3.6cm measurements with a deconvolved size of $0.19'' \times 0.12''$ (PA= 129°).

³The NASA Infrared Telescope Facility is operated under contract by the University of Hawaii.

3.2. Dense neutral gas associated with stars B,C, and D

What is the origin of the emission from B,C, and D? By analogy with the Orion nebula, one suspects that these sources are externally ionised neutral condensations being photoevaporated by the intense UV field of the O7.5III star HD 164492 A. The argument that this is so proceeds similarly to those of Garay et al. (1987) Churchwell et al. (1987) applied to the proplyds first detected in radio continuum in the Orion nebula.

The flat spectra of sources B,C, and D indicate that their radio continuum arises from optically thin free-free emission. For $T \approx 8000$ K, the volume emission measures are $n_e^2 V \sim 1 \times 10^{57} \text{ cm}^{-3}$, and for the emission to be optically thin the characteristic scale R of the emission region $\gtrsim 50$ AU. If this region is a roughly constant-density compact HII region, this scale represents the outer boundary. However, the gas is then gravitationally unbound to the central star and the HII region would expand on a time scale of ~ 30 yr. On the other hand, if the emitting region is an ionized wind with $n_e \propto r^{-2}$, the emission is dominated by the innermost radii and R corresponds to the *inner* boundary. An ionized stellar wind can be discounted, because then $R \ll 50$ AU, and the mix of optically-thin and optically-thick contributions at any given frequency produces a $\nu^{0.6}$ spectrum; further the source would be much weaker than observed. Thus we conclude that the emitting region is an ionized wind that is photoevaporated from a reservoir of neutral material near the star.

The neutral reservoir cannot be too large as sources B and C are unresolved and source D is barely resolved. Adopting a distance of 1.7 kpc to M20, the geometric mean of the semi-major and semi-minor axes of source D (see Table 1) is $R \approx 130 \text{ AU}$, and the corresponding upper limit on sources B and C is 80 AU. The neutral reservoir will be even smaller, and is therefore clearly associated with the star.

The O7.5III star HD 164492 A is likely to be the dominant source of the ionizing photons. An O7.5III star emits 9.6×10^{49} ionizing photons s^{-1} (Panagia 1973), so that the total ionizing flux incident on a 130 AU radius target at the projected distance of star D (≈ 0.095 pc) is $1.1 \times 10^{45} \text{ s}^{-1}$. This is comparable to the hydrogen recombination rate of source D, $6.6 \times 10^{44} \text{ s}^{-1}$. The recombinations in source B and C are also consistent with this hypothesis. Note, however, that stars HD 164492 B,C, and D are of spectral type B (Kohoutek et al 1999) and produce $\sim 10^{45}$ Lyman continuum photons s^{-1} or more, so they may contribute significantly to the ionization if enough photons can intercept the nearby neutral material.

Our observations do not determine the distribution of the neutral material associated with stars B,C, and D, but we speculate that it is in circumstellar disks, as for the “proplyds” in Orion.

3.3. Embedded EW Dust Lane in M20

A $\lambda 6\text{cm}$ grayscale image with resolution of $2.3'' \times 1.1''$ (PA= -80°) and an optical image based on the Palomar Sky Survey are compared in Figures 3a and b. The prominent elongated dust lanes to the SW, SE and NW of the optical image have no counterpart in radio, indicating that these dust features lie in front of the HII region. However, there is a remarkable EW dark radio feature which closely mimics the shape of the optical dust lane seen to the SW of the central hot star in Figure 3b near $\alpha, \delta(1950) = 17^{\text{h}}59^{\text{m}}17^{\text{s}}, -23^{\circ}02'50''$. Figure 4 shows a NS slice cut across this feature in the 6cm radio image. The radio continuum emission is depressed by a factor of 3 where the optical nebula appears to be crossed by an EW dark dust lane with a thickness of about $40''$ (0.3 pc). The correlation between reduced radio emissivity and the optical dust lane is evidence for the dust lane being embedded within the nebula.

Other examples of dark features are also apparent in the inhomogeneous large-scale distribution of ionized gas beyond the inner region shown in Figure 3. These dark features are particularly noticeable as broken shell-like structures surrounding the $6'$ size of the nebula and correlate with the distribution of the HCO^+ $J=1-0$ emission from the nebula presented by Cernicharo et al. (1998). We also note a column of dark feature labelled as dark shadow within the nebula to the east of TC1. These dark features are unlikely to be produced by a lack of short uv spacing data but are instead due to dense 10^4 cm^{-3} column of gas arising from the surface layer of the molecular cloud and causing the HII region to become ionization bounded. The dearth of emission from a series of dark features including the EW feature, as best represented in Figure 3a, are interpreted to be the peaks of dense gas shielding the ionizing flux arising from the central hot star. These columns of dense gas are responsible to reduce the emission measure $n_e^2 L$ where n_e and L are the electron density and the path length.

3.4. Ionized Rims of TC1 and TC2

Figure 5 shows total intensity contours over the central part of the HII region at $2.3'' \times 1.1''$ resolution (PA = -80°). The two extended ionized features to the NW and SE are associated with two bright point-like condensations of dust emission at 1.3mm denoted TC1 and TC2 by Cernicharo et al. (1998). High velocity broad wings in the HCO^+ emission from TC1 and a jet-like HH feature associated with TC2 led Cernicharo et al. to suggest that these condensations are associated with protostars. The age of these condensations are estimated to be about 10^4 yrs and therefore formed after the birth of the HII region. The extended photoionized features in Figure 5 delineate the ionized rims of TC1 and TC2 facing the central hot star. High resolution WFPC2 observations of TC2 using a number of spectral lines was recently reported by Hester et al. (1999) who interpret the ionized layer of TC2 as a photoionizing photovaporative flow. The typical flux density of the ionized rims of TC1 and TC2 is about 0.5 mJy/beam which corresponds to $n_e \approx 2 \times 10^3 \text{ cm}^{-3}$.

4. Discovery of a Supernova Remnant and two Shell-like Features

4.1. G7.06–0.12: A Barrel-shaped SNR

Figure 6 shows a large-scale grayscale image of M20 and its immediate vicinity at 20cm (D array only) with a resolution of $59.1'' \times 33.7''$ (PA = -2°). We note the prominent W28 SNR to the SW and report here a newly discovered shell-type SNR, G7.06-0.12, with a diameter of $13'$ adjacent to the NW rim of M20. Radio continuum measurements at 6cm show linearly polarized emission at the northern rim of M20 near $\alpha, \delta(1950) = 17^h 59^m 22^s, -22^\circ 55'$. The degree of polarization is about 28% at 6cm based on D array data with a resolution of $29.8'' \times 14.3''$ (PA = -27°). This radio source has no obvious optical counterpart and is a previously uncataloged, synchrotron emitting SNR.

Further evidence that G7.06-0.12 is a SNR is provided by its morphology, revealed in the contour map of the 20cm image centered on the remnant and displayed in Figure 6a. Here G7.06–0.12 is revealed as a classic barrel shaped SNR aligned roughly with its major axis parallel to the Galactic equator (Gaensler 1998). The western rim of the barrel is more extensive and is about 3-4 times brighter than the eastern rim, which protrudes north of M20 near $\alpha = 17^h 59^m 25^s$. We also note several clumps of 20cm continuum features to the north of 7.1–0.1 and a $8'$ elongated structure running north-south toward the center of the

SNR.

Finally, the identification of G7.06–0.12 as a barrel-shaped SNR is confirmed by its nonthermal continuum spectrum and morphology as determined from complimentary 90cm observations. Figure 7b is D array, 90cm contour image centered on the bright SNR W28 with an angular resolution of $5.5' \times 2.6'$ (PA=13.4°). Protruding north of the W28 SNR near $\alpha = 17^h58.5^m$ is the western half of G7.06–0.12, whose eastern half is now smothered by M20 centered near $\alpha = 17^h59.3^m$. G7.06–0.12’s barrel shaped morphology is also revealed on reinspection of the higher resolution ($\sim 20''$) wide-field 90cm image centered near the SNR G5.4-0.1 (Frail, Kassim, and Weiler 1994). The 90cm image is dominated by W28, whose integrated flux is 350 ± 50 Jy.

Confirmation of the nonthermal spectrum of G7.06–0.12 comes from comparing the integrated flux of the well defined western half of the barrel, giving an average of ~ 3.9 Jy as obtained from the two 90cm measurements and ~ 1.9 Jy from the 20 cm image. This yields the canonical $\alpha \sim -0.5 \pm 0.15$ nonthermal spectrum of a typical shell-type SNR, as expected. The images are sufficient to confirm that the eastern half of G7.06–0.12 is also nonthermal, but higher resolution 90cm data is required to determine the spectrum of either side of the barrel more accurately than this. It is interesting to note that the integrated flux of M20 from our D array 90 cm map, which includes some flux from the eastern half of G7.06–0.12, is 11 ± 2 Jy. Together with the 14 ± 3 Jy integrated flux present on our 20 cm map this indicates a slightly inverted spectrum revealing that the HII region has started to become optically thick at 90 cm as is common.

While the eastern rim of G7.06–0.12 merges with the northwest segment of M20, there is no morphological evidence for the interaction of the SNR and M20. We cannot rely on $\Sigma - D$ relationship to estimate the distance to G7.06–0.12 (Green 1991) but VLA observations at 74 MHz should be able to determine the relative positions, since at that frequency M20 would have become completely optically thick and it would be apparent whether the eastern side of the barrel was being absorbed or not. We note this region of the Galaxy is rich in having a number of HII complexes (M8, M20), the SNR W28 expanding into an adjacent molecular cloud (e.g. Wooten 1981) as well as a young star cluster NGC 6514. Thus, it is plausible that SNR G7.06–0.12 is associated with the young cluster, but further studies are needed.

4.2. G6.67-0.42: A Nonthermal Shell-type Feature

An additional new radio continuum source identified in this rich region of the Galaxy is G6.67–0.42, located $20'$ south of M20 as labelled in Figure 6. G6.67–0.42 is clearly distinct from W28 and shows a protruding feature in the eastern part of W28 near $\delta(1950) = -23^{\circ}23'$. This feature which is curving convex downwards is another previously, unidentified source. It’s morphology is clearly shell-like, as indicated from the 20 cm image displayed in Figure 7a. However the limitation of the 20 cm field of view together with the confusion from W28 allows only a northeastern fragment of an apparently circular shell to be clearly delineated. High-resolution observations at 20cm reveals this new feature which otherwise would have been associated to W28 in earlier low-resolution measurements. The 90cm image shown in Figure 7b shows G6.67–0.42 merged with the eastern part of the shell in W28.

Estimating the spectrum of G6.67–0.42 was done by convolving the 20 and 90cm images to the same resolution $328.8'' \times 157.6''$. The spectrum is estimated to be $\approx -0.35 \pm 0.15$ from the peak flux and integrated flux of the shell fragment at 20 and 90cm. The nonthermal emission could be supplied or be part of the W28 remnant itself, such as resulting from a so-called ”blow-out” where the main blast wave has encountered a lower density ISM region. However, the geometry of the weaker shell-like feature and its

distinct structure from W28 is not classic blow-out morphology in that its implied center of curvature is significantly different than that of the main W28 shell. Future observations should clarify if the nonthermal shell fragment is either part of W20 or yet another previously unidentified shell-type SNR.

4.3. G6.83-0.21: A Shell-type Structure

Lastly, we detect a weakly emitting shell-like source G6.83–0.21 lying between M20 and W28, as labelled in Figure 6. This source lies in a difficult region of our 20cm image where a “negative bowl” surrounding both W28 and M20 suppresses any emission arising from this weak source. In spite of this difficulty, we note a shell source with a diameter of about $15'$ lying between the northern and southern edges of W28 and G7.06–0.12, respectively. The eastern edge of G6.83–0.21 is brighter and has a typical flux density of about 4 mJy beam^{-1} above the negative depression at a level of -6 mJy beam^{-1} .

It is difficult to determine the nature of G6.83–0.21 because of the lack of spectral and polarization information. However, two observational anomalies, described below, imply that G6.83–0.21 is possibly a distinct shell-type SNR. The bright compact source G6.833–0.093 and the pulsar PSR 1758-23 lie at the geometrical center of the shell source G6.83–0.21. An association between PSR 1758-23 and the W28 SNR has been suggested on the basis of age, even though the pulsar lies outside the W28 shell. This hypothesis has the difficulty that it has a much larger dispersion measure than expected if the pulsar were placed 2kpc away (Kaspi et al. 1993), although Frail, Kulkarni and Vasisht (1991) have argued that the large dispersion and scattering of the pulses from PSR 1758-23 are caused by a dense screen of ionized gas located along the line of sight. Another anomaly is the kinematics of the OH(1720 MHz) masers observed across the northern part of W28 (Claussen et al. 1998). OH(1720 MHz) masers have recently been identified as a signature of SNRs interacting with molecular clouds (e.g. Frail, Goss & Slysh 1994; Lockett, Gauthier & Elitzur 1999; Wardle 1999). The kinematics of these masers are generally found to be similar to the systemic velocity of molecular clouds into which SNRs are expanding. Claussen et al. (1998), however, notice an exception in W28, where the masers fall into low and high velocity groups. Two molecular clouds have been observed toward W28 at 7 and 17 km s^{-1} in various molecular lines (Wooten 1981). To explain this velocity difference, Claussen et al. (1998) suggest that the entire low-velocity molecular cloud has been accelerated by the SNR shock along our line of sight.

The above anomalies may be resolved if G6.83–0.21 is a shell-type SNR associated with the PSR 1758-23 and is interacting with a distinct 7 km s^{-1} molecular cloud. The distance to G6.83–0.21 is difficult to estimate but it has to be placed at a larger distance than 2 kpc to be consistent with the high dispersion of pulsar signals. Future observations of G6.83–0.21 should be important to clarify if this feature is a confusing source in this complex region of the Galaxy or it is a new member of the class of SNRs with associated OH(1720 MHz) masers lying within the inner several degrees of the Galactic center (Yusef-Zadeh et al. 1999).

F. Yusef-Zadeh’s work was supported in part by NASA. Basic research in radio astronomy at the Naval Research Laboratory is supported by the Office of Naval Research.

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Figure captions

Fig. 1.— Contours of total intensity at $\lambda 3.6\text{cm}$ with a spatial resolution of $0.63'' \times 0.45''$ (PA= 80°) with an rms noise of $33\mu\text{Jy}$. The levels are set at -3, 3, 5, 7, 9, 11, 13, 15, 20, 25, 30, 40 times the rms noise.

Fig. 2.— Exploratory NSFCAM images (log-scaled) of the central cluster of M20. The visible components of the multiple star HD 164492 are labelled in the J image. Field of each image is approximately $80'' \times 80''$, with N up and E left. The dark spots are due to stars in the nearby blank sky image which is used to subtract the background.

Fig. 3.— A $\lambda 6\text{cm}$ radio continuum image (3a) with a resolution of $2.3'' \times 1.1''$ (PA= -8°) is shown against a Palomar image from Digital Sky survey (3b). Both images show an identical region and prominent features are identified in both images.

Fig. 5.— A close up view of figure 3a showing TC1 and TC2 regions with contour levels set at -4, 4, 6, 8, 10, 12, 14, 16 times $40\mu\text{Jy beam}^{-1}$.

Fig. 6.— Greyscale image of the M20 region $\lambda 20\text{cm}$ with a spatial resolution of $65.2'' \times 39.3''$ (PA= -34°) identifying prominent sources. The primary beam correction has not been applied to this image.

Fig. 7.— Contours of total intensity at $\lambda 20\text{cm}$ with a spatial resolution of $65.2'' \times 39.3''$ (PA= -34°) with an rms noise of 1 mJy. The levels are set at -3, 3, 5, 7, 9, 11, 13, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 100, 120, 140, 170, 200, 250, 300, 350 times 2 mJy beam^{-1} .

Fig. 8.— Contours of $\lambda 90\text{cm}$ emission obtained from D-array configuration of the VLA. The angular resolution is $5.5' \times 2.6'$ (PA= 13.4°) and the rms noise is about 200 mJy beam^{-1} . The peak emission is 14.2 Jy beam^{-1} and contour levels are at $100\text{ mJy beam}^{-1} \times -8, -6, -4, -2, -1, 1, 2, 4, 6, 8, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130$.

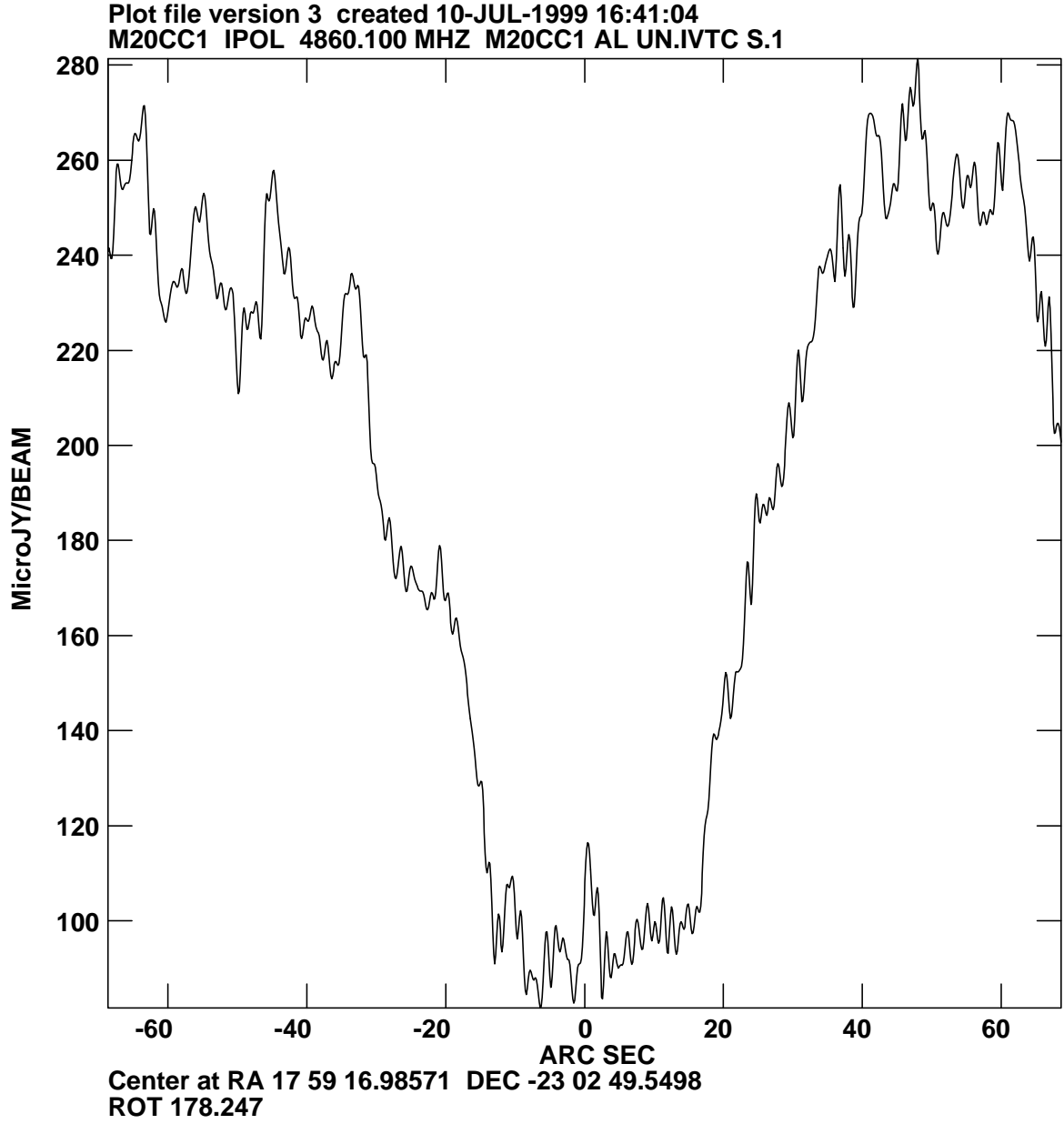


Fig. 4.— A slice cut along the EW dust lane at 6cm centered at $\alpha, \delta(1950) = 17^h 59^m 17^s, -23^{\circ} 02' 49.5''$ at the position angle of 178° .

TABLE 1
VLA AND HIPPARCOS POSITIONS OF M20 STARS

Source Designation	α_{1950} (h m s)	δ_{1950} ($^{\circ}$ ' ")	S_p (mJy)	Deconvolved Size		
				major (")	minor (")	PA ($^{\circ}$)
M20-VLA-B	17 59 21.52 \pm 1E-3	–23 01 48.98 \pm 1E-2	0.61	–	–	–
M20-VLA-C	17 59 20.95 \pm 3E-4	–23 02 03.8 \pm 3E-3	2.46	–	–	–
M20-VLA-D	17 59 20.78 \pm 3E-4	–23 02 03.38 \pm 3E-3	2.24	0.19 \pm 0.03	0.12 \pm 0.06	129 \pm 27
M20-HIP-A	17 59 21.38	–23 01 54.8	–	–	–	–
M20-HIP-B	17 59 21.53	–23 01 48.9	–	–	–	–
M20-HIP-C	17 59 20.96	–23 01 03.8	–	–	–	–